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X-ray Fluorescence Measurements of Turbulent Methane-Oxygen Shear Coaxial Flames

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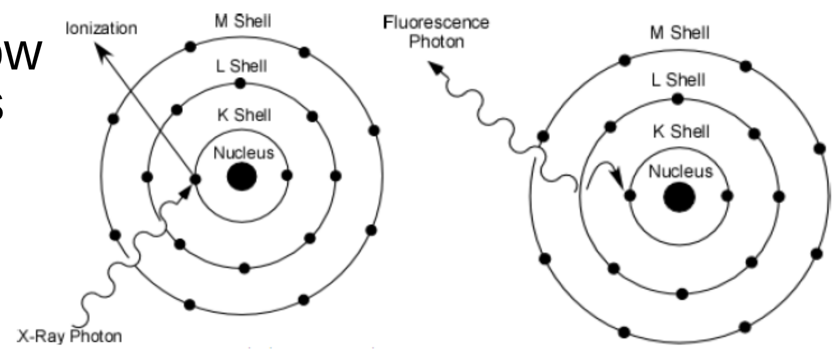
Motivation

- **Next generation Air Force propulsion systems will operate in combustion regimes for which fundamental knowledge and validation data is currently limited**
- **Experimental methods that can measure key flame properties under relevant conditions are needed to improve our understating of these regimes, which can then be integrated into models**
- **X-ray diagnostics have a number of advantageous properties that make them attractive for quantitative measurements in complex flames**
- **Goals for this effort:**
  - Demonstrate the use of X-ray fluorescence to quantitatively measure flame properties in a propulsion relevant flame
  - Concentrate on high-energy-density turbulent flames relevant to liquid rocket engines
  - Explore the use of two different tracers, Argon & Krypton
  - Identify a path forward to apply these techniques to increasingly complex flames

X-Ray Diagnostics

- **X-ray diagnostics have some advantages over laser diagnostics**
  - Insensitive to chemical bonding
    - Interactions are with inner-shell electrons
  - X-rays undergo very little refraction eliminating beam steering and multiple scattering effects
  - Quantitative measurements can be made with minimal corrections required
- **Two types of X-ray diagnostics radiography and fluorescence**
  - Radiography has been widely used in sprays to obtain mass density measurements close to injector exit where other spray diagnostics struggle
  - Fluorescence is better suited to low absorption flow fields such as gas phase mixing and combustion
  - Both can be used in reacting and nonreacting flowfields

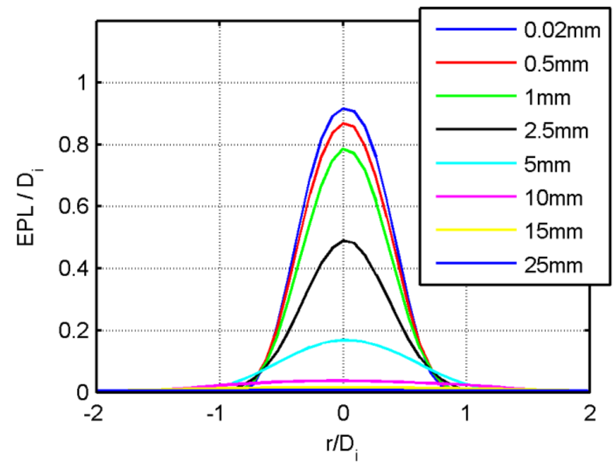


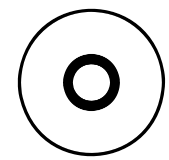
Radiography- Radial EPL Profiles

- **Near-injector EPL profiles have elliptical shape expected from a solid liquid jet**
- **Closest measurements were made 0.02 mm downstream**
- **EPL decreases axially as liquid core is atomized and droplets are accelerated**
  - EPL is a function of local mass flux and velocity

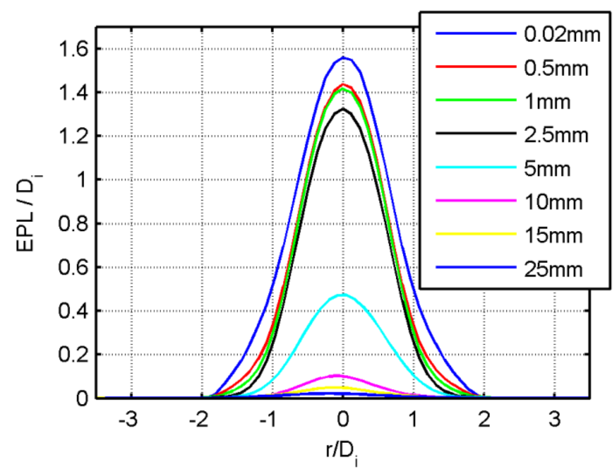
$$EPL \approx \frac{\Phi L_P}{U_l \rho_l}$$

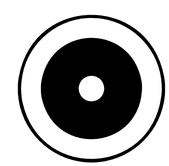
- **Shoulders on SC1-10 profiles due to a liquid in the post tip recirculation zones**



SC4-10, *J*=9.1

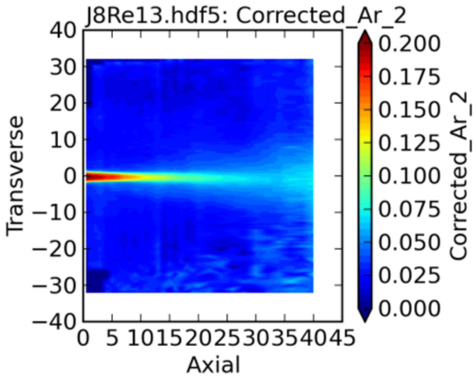


SC1-10, *J*=9.6

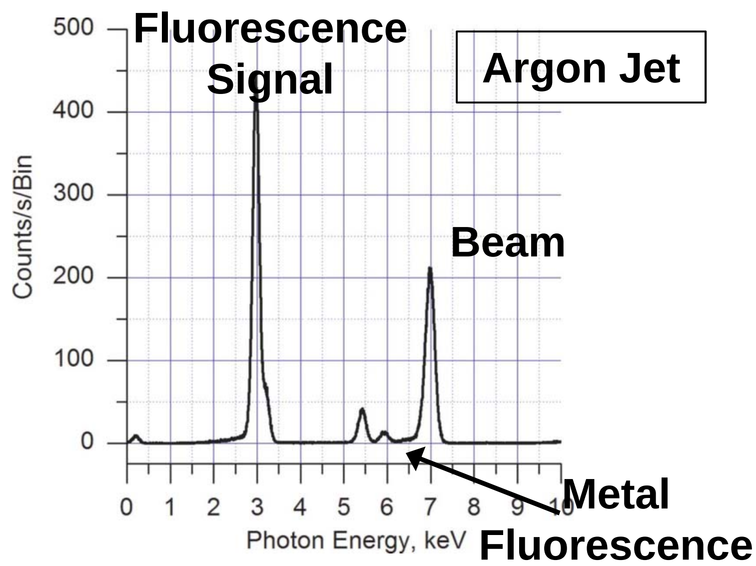
X-Ray Fluorescence

- **Tracer elements are conserved in reacting flowfield**
  - Local pressure, species concentrations and temperature have no impact on X-ray fluorescence other than influence on local tracer density
  - Nobel gases such as Ar and Kr and metals such as Fe, Zn, & Br can be used as tracers (carbon tetrabromide CBr4 work well with liquid fuels)
- **X-ray Fluorescence has a number of disadvantages**
  - Requires a synchrotron X-ray source
  - With current detector is a pathlength integrated point measurement
  - Images are built from raster scanning flowfield
  - Low speed, current maximum sampling rate on the order of 100 Hz
  - To back out mixture fraction both oxidizer and fuel streams must be traced which was not possible for this round of measurements but will be in the future

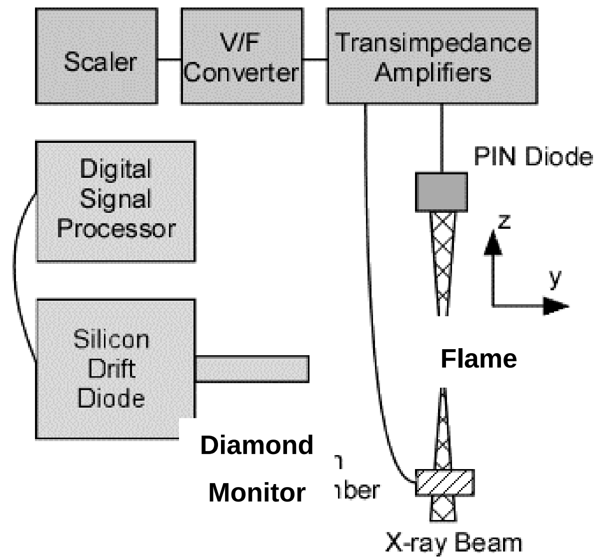


Diagnostic Technique

- **Simultaneous fluorescence and absorption measurement**
- **Absorption measurement used to account for beam attenuation**
- **Kr & Ar data corrected for changes in beam intensity, beam attenuation and detector dead time.**
- **Ar data corrected for signal trapping**
- **Cold-flow scan near nozzle exit used for normalization**

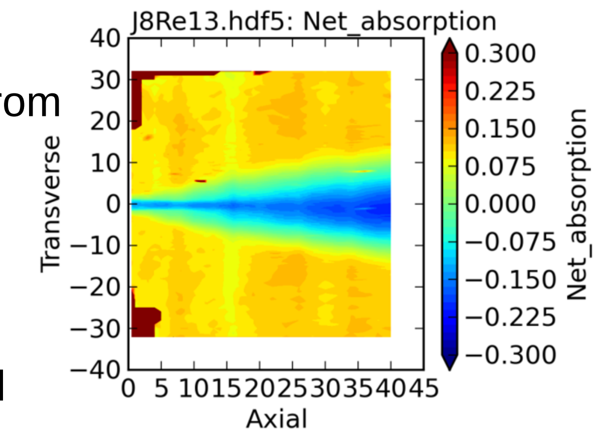


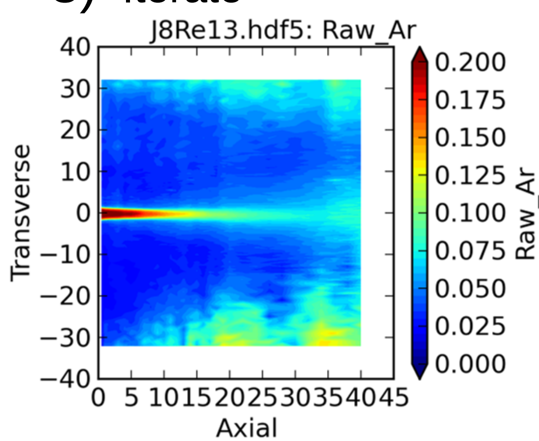
Tracer	Ar	Kr
Atomic Mass (amu)	39.95	83.80
Threshold Energy (keV)	3.21	14.33
Fluorescence Energy (keV)	3.0, 3.2	12.6, 14.1
Fluorescence Efficiency	0.12	0.60
Beam energy (keV)	6.7	15
X_{tracer}	10 %	3 %

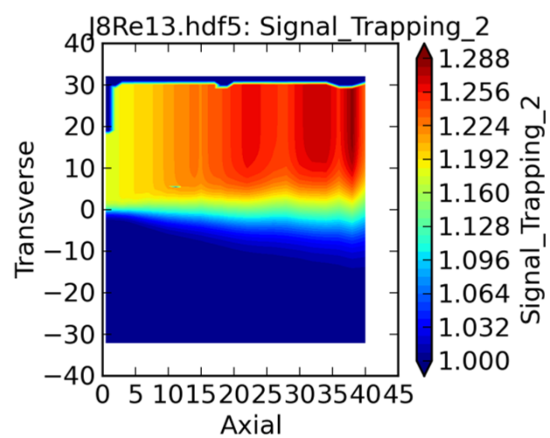


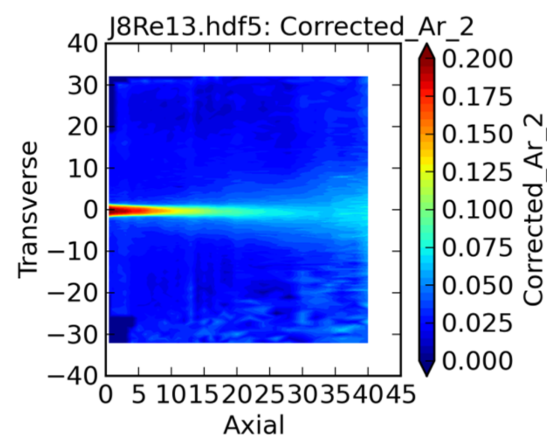
Signal Trapping Correction

- **Signal Trapping correction is applied to each transverse scan**
  1) Assume axisymmetric and perform fit to fluorescence data
  2) Scale radiography signal from incident photon energy (6.7 keV) to the fluorescence photon energy (3.0 kev)
  3) Assume axisymmetric and perform fit to radiography data
  4) Compute 2D distributions of fluorescence and absorption from the fits computed in Steps 1 & 3
  5) Use 2D absorption distribution to compute absorption between point and fluorescence detector
  6) For each beam path determine mean signal trapping
  7) Use signal trapping estimate to correct fluorescence signal
  8) Iterate



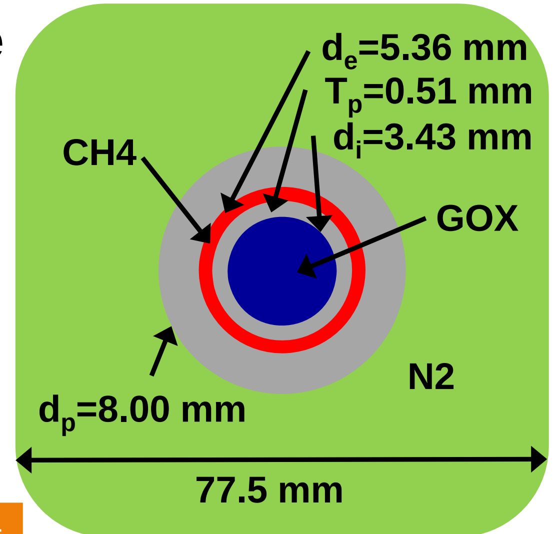




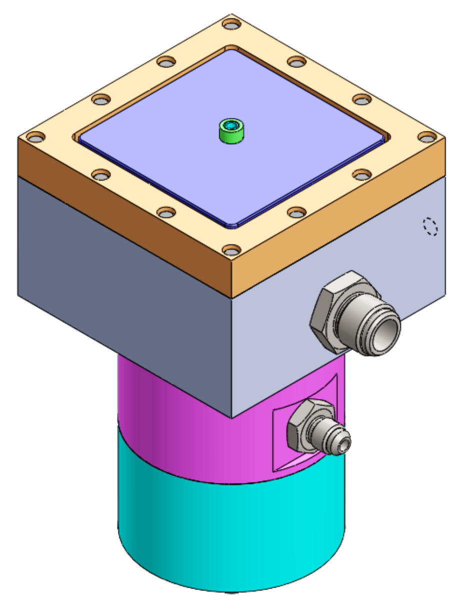


Flame Geometry & Test matrix

- Shear coaxial flame chosen due to its relevance to liquid rocket engines and it's compactness
- Flames sized for Re>10,000 with minimal propellant flow rates
- Nitrogen coflow used to isolate the flame
- Single Geometry: d_e= 5.36 mm, d_i=3.43 mm, & T_P=0.508 mm

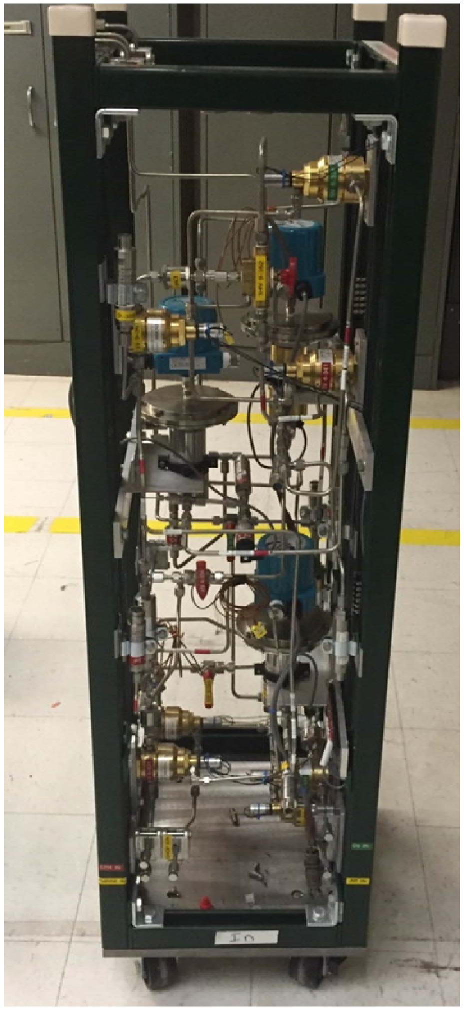


Case	Tracer	Tracked Stream	Type	J	Re	U_F, m/s	U_O, m/s	U_C, m/s	$\dot{m}_F$, g/s	$\dot{m}_O$, g/s	Y_{Tracer}
J5KR	Kr	O2	Flame	5.09	14,000	54.6	17.2	0.80	0.261	0.213	0.073
J5MKR	Kr	CH4	Flame	6.54	10,000	41.2	11.9	0.98	0.221	0.127	0.073
J5CKR	Kr	O2	Cold	5.15	14,000	54.2	17.0	0.80	0.263	0.214	0.075
J5AR	Ar	O2	Flame	5.08	14,000	54.6	17.3	0.80	0.260	0.212	0.121
J8AR	Ar	O2	Flame	8.00	11,000	48.0	12.1	0.98	0.228	0.148	0.120
J10AR	Ar	O2	Flame	10.0	11,000	49.3	11.1	0.96	0.234	0.137	0.122

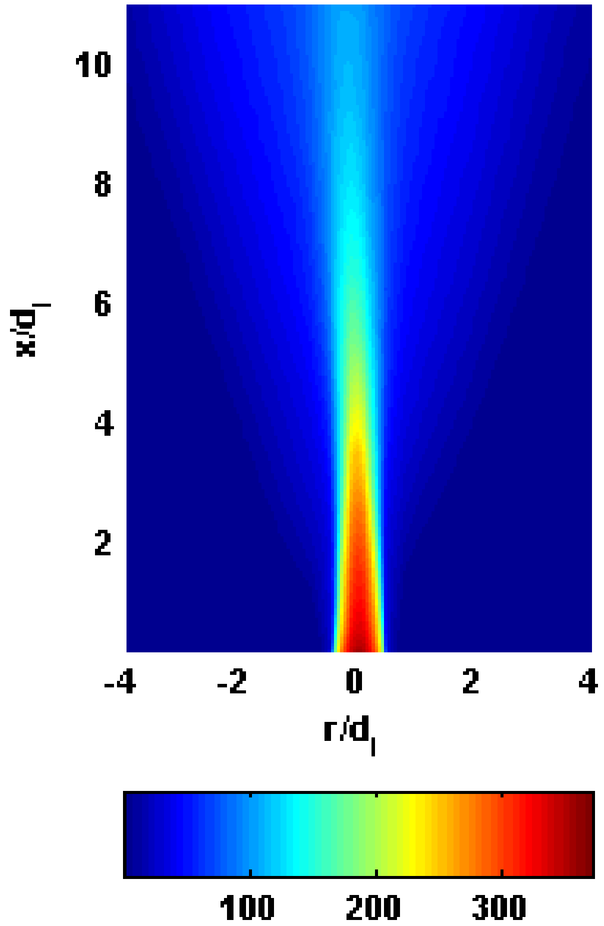


Flow System

- **Constructed new propellant flow cart with fuel, oxidizer and tracer gas flow circuits**
  - Runs from k-bottles
  - Complete remote operation
  - Sonic nozzles used for mass flow measurements
  - System integrated with our Mobile Flow laboratory
- **Self contained mobile system capable of delivering up to 1 kg/s of H_2O & GN_2 at pressures in excess of 200 atmospheres**
  - Requires only power, LN_2, and exhaust from host facility.
  - System fully rated to 408 atm (Allows more GN_2 storage)
  - Dedicated control & data acquisition systems
  - System is on wheels and can be assembled in under 2 days
  - Consists of an electronic rack, instrumentation and control cart, tank and flow cart, and LN2 pump and vaporizer



Krypton vs. Argon

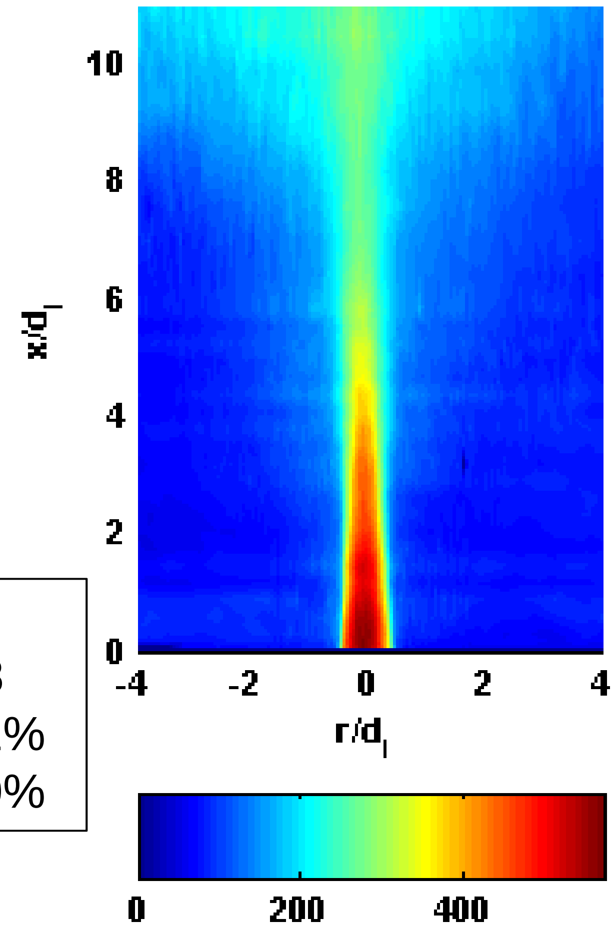


Projected Kr Density, ng/mm²

J5KR
J=5.09
Y_{Kr}=7.3%
X_{Kr}=3.0%

Kr Tracer in GOX

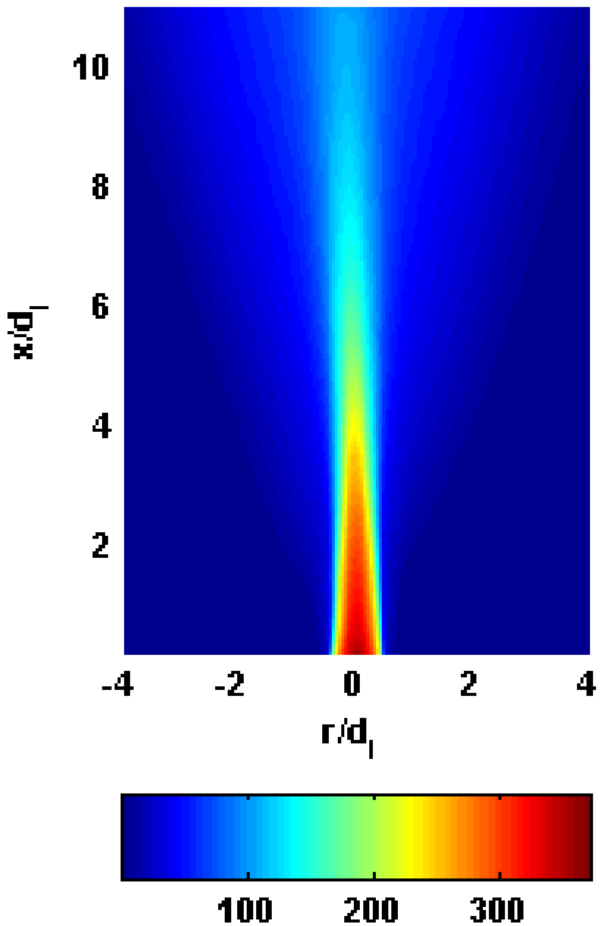
J5AR
J=5.08
Y_{Kr}=12.1%
X_{Kr}=10.0%



Projected Ar Density, ng/mm²

Ar Tracer in GOX

Krypton J5RE15 Results

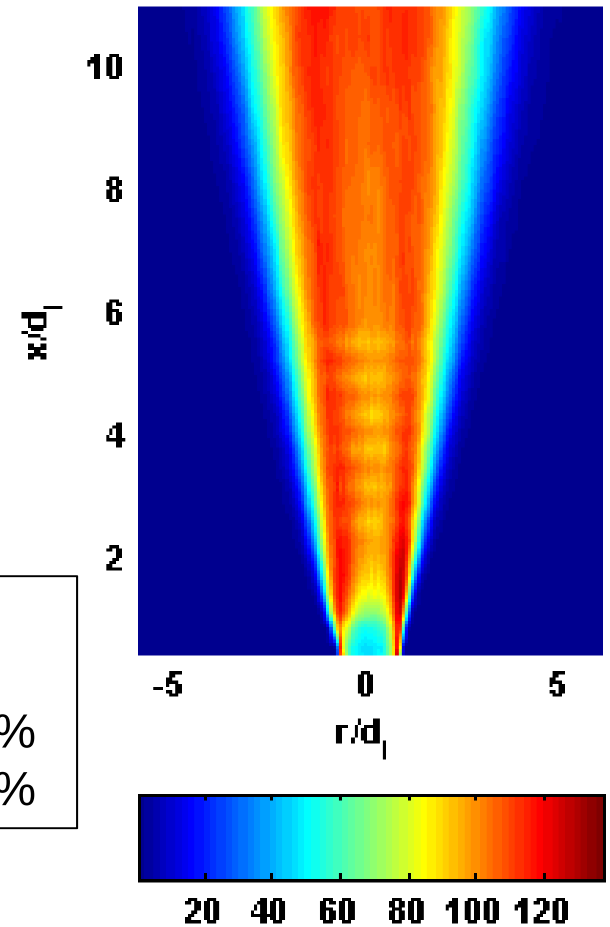


Projected Kr Density, ng/mm^2

Kr Tracer in GOX

J5KR
J=5.09
Y_{Kr}=7.3%
X_{Kr}=3.0%

J5AR
J=5.08
Y_{Kr}=12.1%
X_{Kr}=10.0%

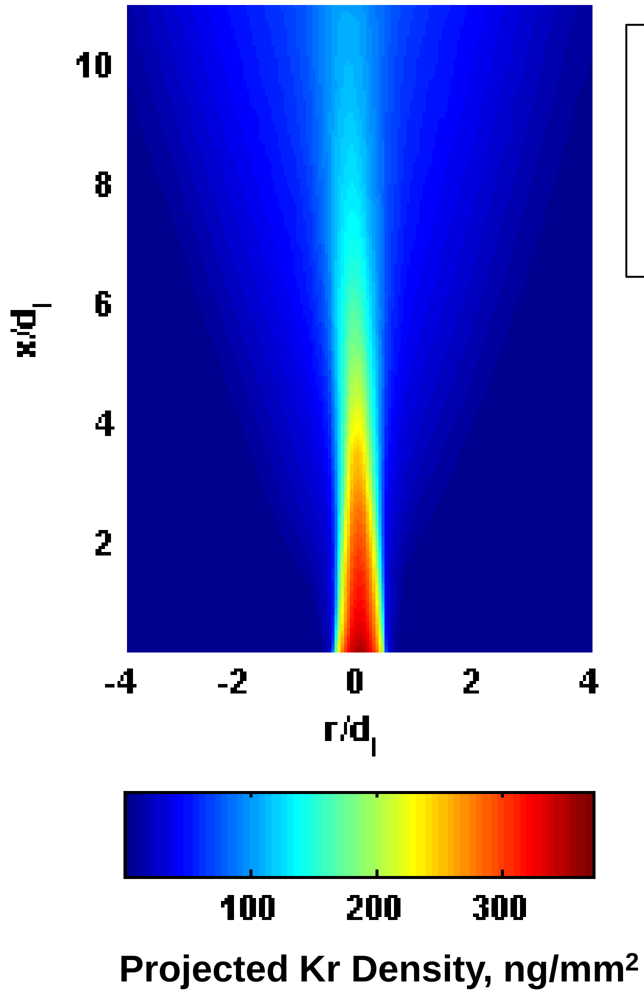


Projected Kr Density, ng/mm^2

Kr Tracer in CH4

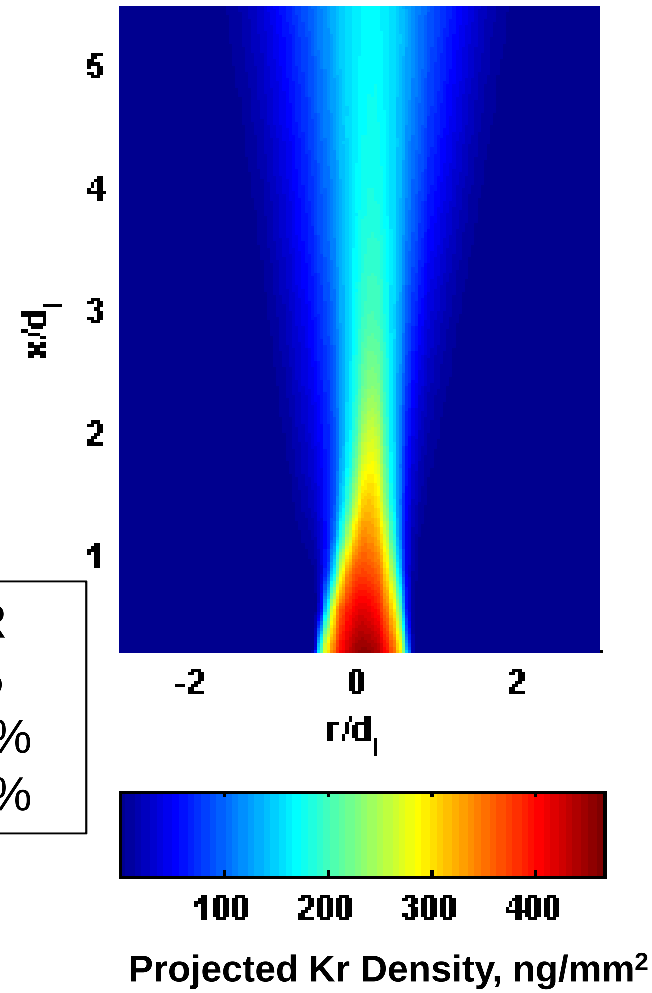
J5RE15 Reacting vs Nonreacting

J5KR
J=5.09
Y_{Kr}=7.3%
X_{Kr}=3.0%



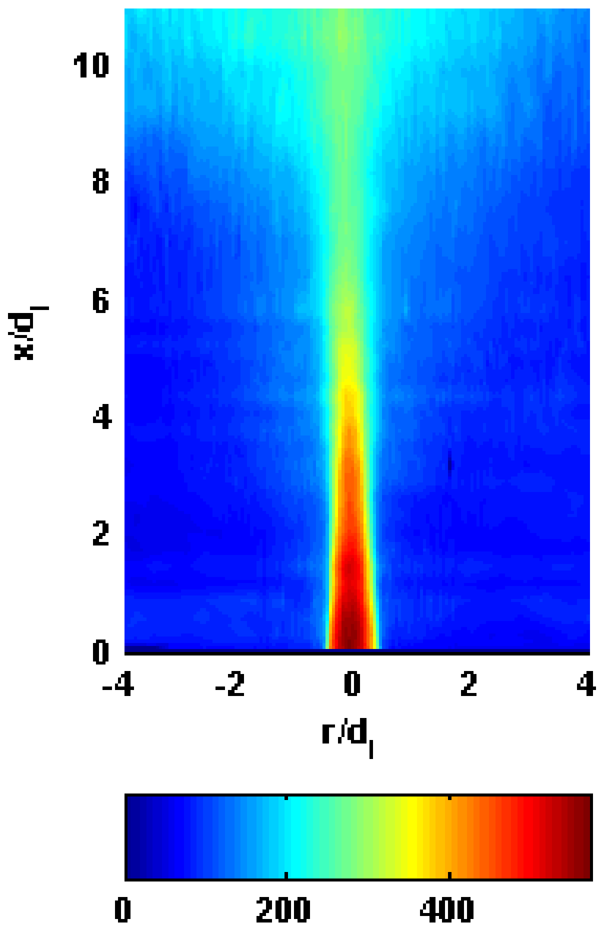
Flame

J5CKR
J=5.15
Y_{Kr}=7.5%
X_{Kr}=3.0%



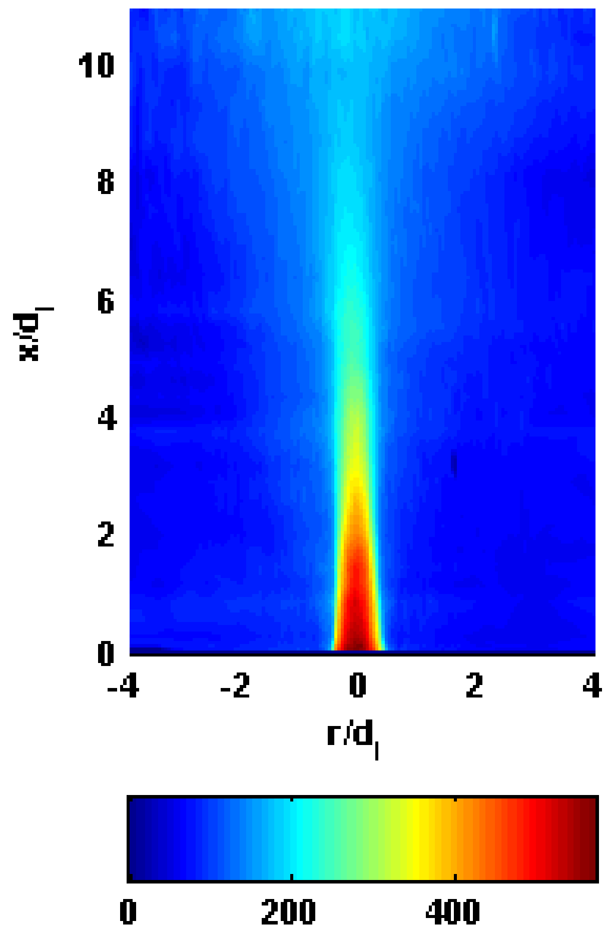
Cold Flow

Momentum Flux Ratio Comparison



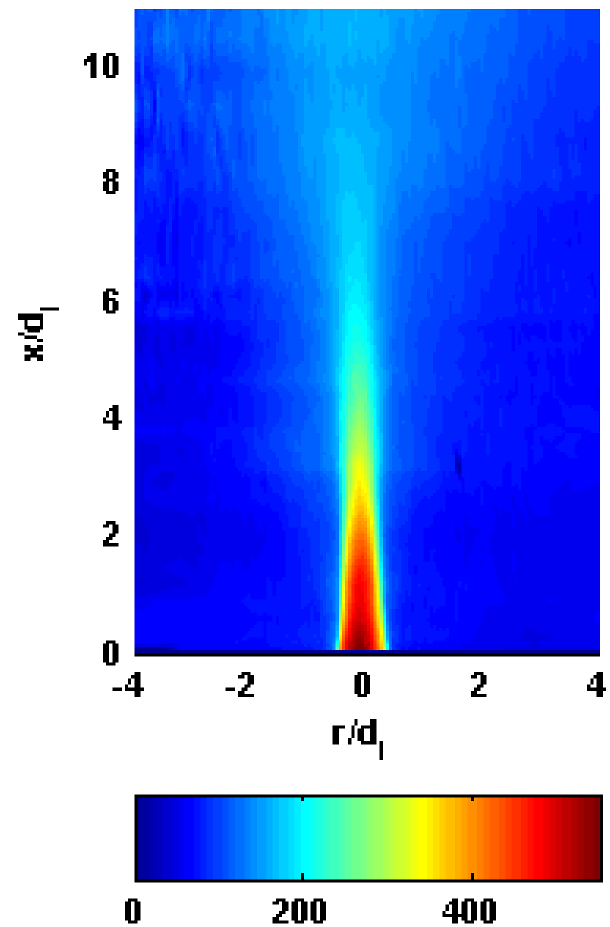
Projected Kr Density, ng/mm^2

J5AR
J=5.08



Projected Kr Density, ng/mm^2

J8AR
J=8.00

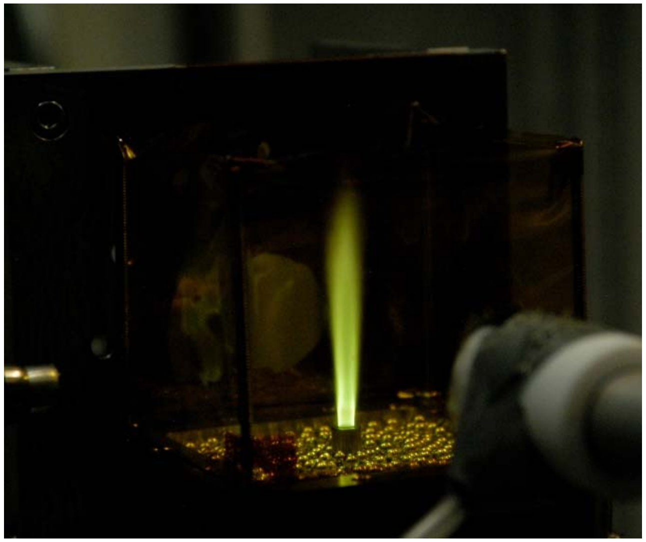


Projected Kr Density, ng/mm^2

J10AR
J=10.00

Future work

- **Apply X-ray fluorescence technique to other propulsion relevant Flame**
  - Multi-phase spray flames
    - Use krypton to track gas phase and carbon tetrabromide for liquid phase
    - Both can be excited at 15 keV
  - Supercritical flames
    - Technique not effected by phase changes
    - Likely limited to around 500 PSI
  - Simultaneous tracking of both propellants in gas phase flames to measure mixture fraction
    - Requires upgrades to beamline
- **Improvements to technique**
  - Polycapillary optic to allow point measurements
  - Use white beam to increase sampling rates and allow imaging



Summary & Conclusions

- **X-ray fluorescence was used to make first of their kind quantitative measurements in a turbulent high-energy density flame**
  - Technique demonstrated on a liquid rocket relevant CH_4/O_2 shear coaxial flame
- **Successfully demonstrated the use of both Ar and Kr as X-ray tracers in flames**
  - Required minimal corrections
  - Ar data had to be corrected for signal trapping and room air Ar background signal
  - Kr shown to be better tracer: No signal trapping, no room air background signal, & significantly higher fluorescence efficiently resulting in lower tracer concentrations
- **Obtained quantitative measurements of tracer concentration**
  - Unable to directly back out mixture fraction but showed it is feasible with upgrades to the beamline
- **Built infrastructure to make flame measurements possible at APS**
  - Significantly decreases cost and time for future flame measurements
- **Future work should focus on achieving simultaneous multiple tracer measurements and conducting measurements in multi-phase flames and supercritical flames**

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